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A frost-point hygrometer installed on the NASA C141 Flying Observatory has been used to measure water vapor in the low stratosphere in a 15-degree latitude band over western United States and the eastern Pacific during the winter of 1974-1975. Measurements at 12.5 km in December 1974 revealed regions of below-normal concentration when compared with a 10-year data period beginning in 1964. Measurements in March 1975 show a further drying of the low stratosphere, with a mixing ratio of water vapor to air mass of less than 2.0 ppm. The decrease was observed over a broad latitude band during several flights and appears representative of the
(Continued)

20. Abstract (Continued)

midlatitudes generally. Measurements over flight paths which were above the tropopause transition layer showed substantial uniformity over long distances. Typical variability in March was 0.5 ppm about a value of 1.9 ppm.

CONTENTS

MEASUREMENTS OF STRATOSPHERIC WATER VAPOR FROM THE NASA C141 AIRCRAFT

INTRODUCTION

Water vapor is important in the chemistry of the stratosphere and must be considered when modeling stratospheric behavior and assessing the effects of aircraft emissions. Water-vapor measurements by the Naval Research Laboratory over more than a decade [1-4] together with measurements by other investigators [5] provide baseline data for assessing the normal vertical distribution of water vapor in the stratosphere and its year-to-year and seasonal variation; however there are few available data for assessing horizontal variation over short time intervals. The purpose of this study was to investigate the horizontal variation using an instrumented aircraft.

In early 1974 a frost-point hygrometer was installed in the NASA C141 Flying Observatory, and measurements of stratospheric water vapor in the low stratosphere and high troposphere were begun in June of that year. The installation and the June measurement have been reported previously [6]. The present report will discuss measurements that were made in the winter of 1974-1975.

OBSERVATIONS

Two flights were made in December 1974 which provided measurements at stratospheric levels. The first flight (Fig. 1) was on December 4, when a deep upper air trough was along the west coast of the United States. The plane left Moffett Field, California, and ascended to 12,500 meters while flying east to Colorado. The 12,500-meter cruise altitude was maintained as the plane flew west from Colorado to the 135th meridian over the Pacific Ocean and back to Moffett Field. During the westward flight at 12,500 meters, or 18.3 kN/m^2 (183 millibars), the plane flew from a pressure ridge over Colorado with a tropopause height of 19.3 kN/m^2 to the pressure trough along the coast, where the tropopause height was 36.2 kN/m^2 or 8000 meters. As the tropopause height decreased along the flight path, the plane at 18.3 kN/m^2 passed through the transition layer separating air of tropospheric characteristics from air of stratospheric characteristics. At the same time, the aircraft crossed the zone of maximum winds, with an accompanying air temperature increase of 20°C. During the southbound leg of the flight over the Pacific a jet stream with 100-knot winds was approached but not crossed.

The mass mixing ratios averaged over 2-1/2 minutes are shown in Fig. 2 for aircraft positions at 15-minute intervals. The mixing ratio just above the tropopause over Colorado was about 7 ppm. As the aircraft flew westward and the separation between cruise altitude and tropopause altitude increased from 300 to 4500 meters, the mixing ratio decreased to 2.5

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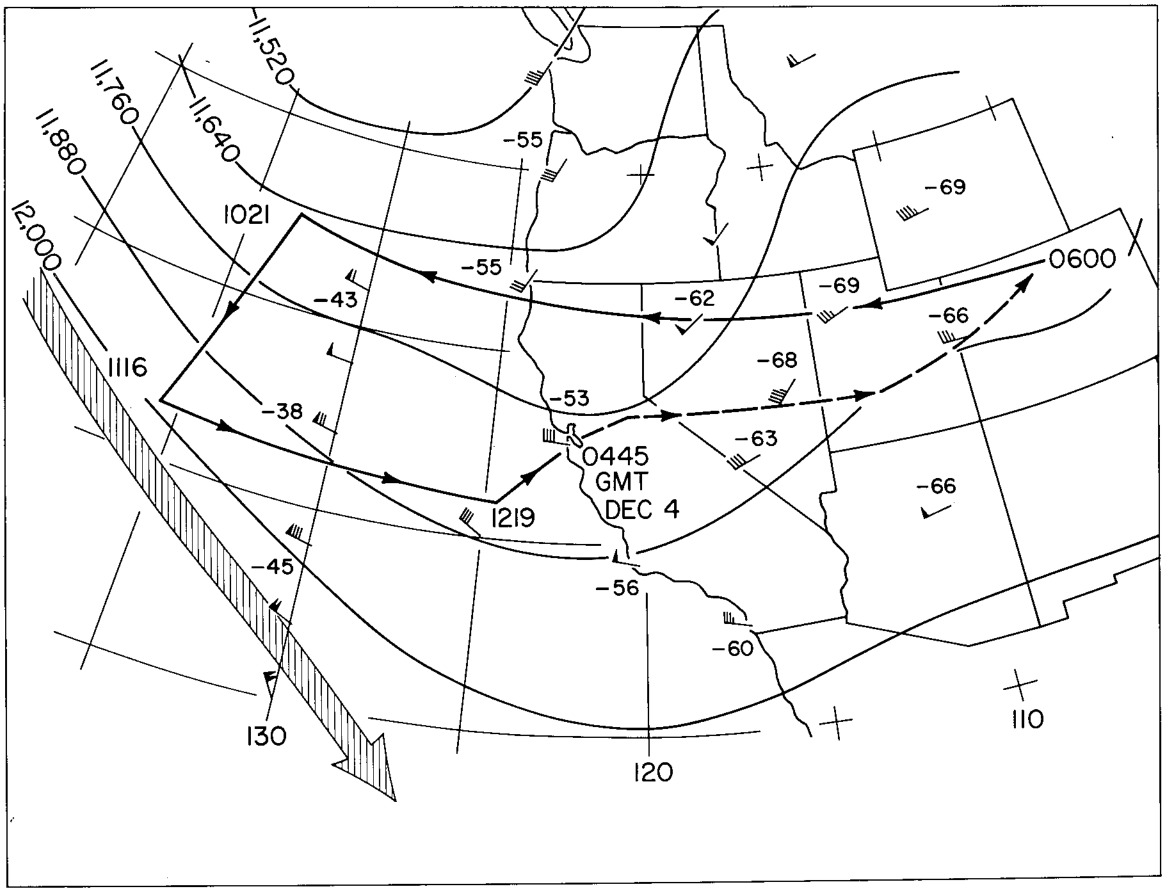


Fig. 1 — The track for the flight of December 4, 1974, and the height contours (heights in meters) analyzed by the National Weather Service for the 20-kN/m^6 (200-millibar) surface for 0000 GMT with winds and temperatures. The solid track represents flight at the 18.3-kN/m^2-pressure height.

ppm. During the southbound cross-wind leg of the flight the mixing ratio become more variable, in the range of 2.1 to 3.0 ppm. The lowest mixing ratios, about 2 ppm, were observed during the close approach to the strong jet stream in the Pacific. When the aircraft flew eastward to Moffett Field and moved away from the jet and into the trough, the mixing ratio returned again to about 2.5 ppm.

Measurements during the descent into Moffett Field indicate the cruising altitude was 300 to 600 meters above the transition layer, where there was a pronounced vertical gradient of mixing ratio. The variability in the western sector of the flight may be evidence of structuring or simply vertical motion in the presence of a vertical gradient.

The second flight occurred 2 days later, when the upper air trough had moved to the middle of the country. The jet stream was well to the south, near the Mexican border. The

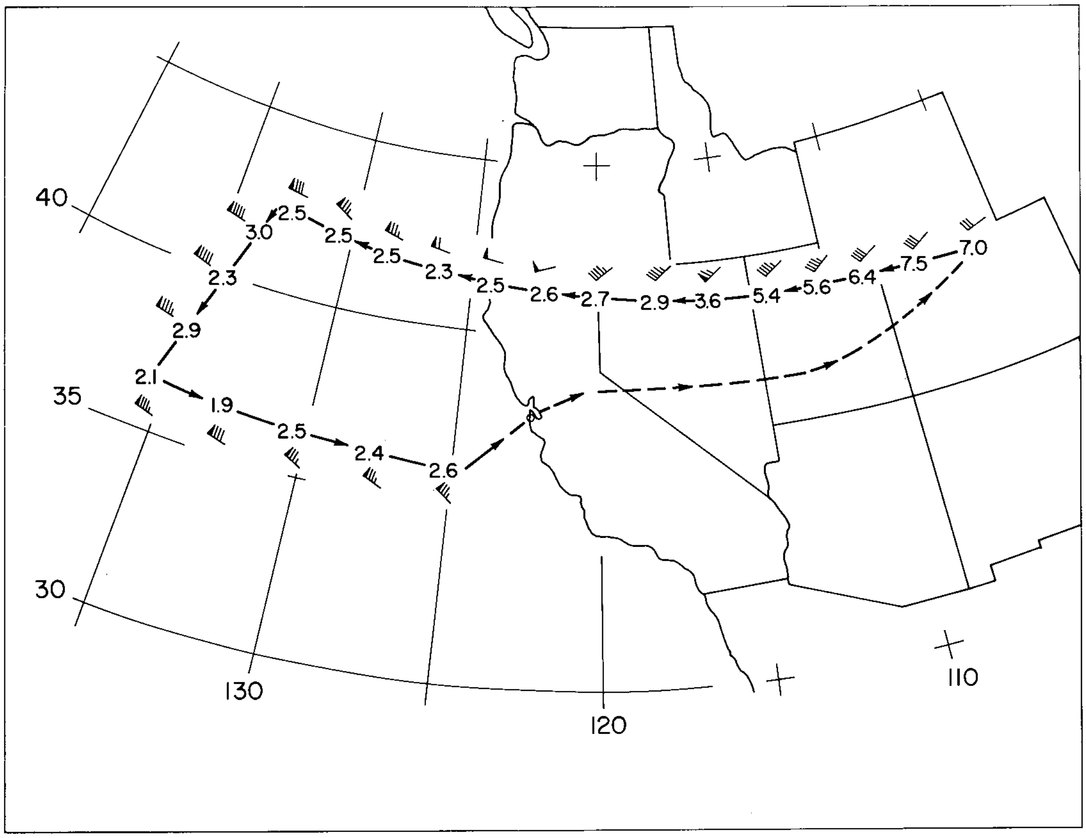


Fig. 2 — The mixing ratio (ppm) of water vapor to air mass and the wind at a 15-minute intervals along the flight track. The solid track represents flight at the 18.3-kN/m^2 pressure height.

flight track (Fig. 3), starting at Moffett Field, was east to Colorado, west to the 130th longitude in the Pacific, east again to Oregon, and south to Moffett Field. The aircraft ascended to 12,500 meters (18.3 kN/m^2) on the way to Colorado and remained at this altitude for the balance of the flight. This flight level was in the stratosphere at all times. A vertical sounding (Fig. 4) of temperature and frost point was obtained during the initial ascent to 11,500 meters which showed the tropopause level at 28.7 kN/m^2. During the 600-meter ascent immediately above the tropopause, the frost point temperature decreased 17°C; this corresponds to an order-of-magnitude drop in the mixing ratio.

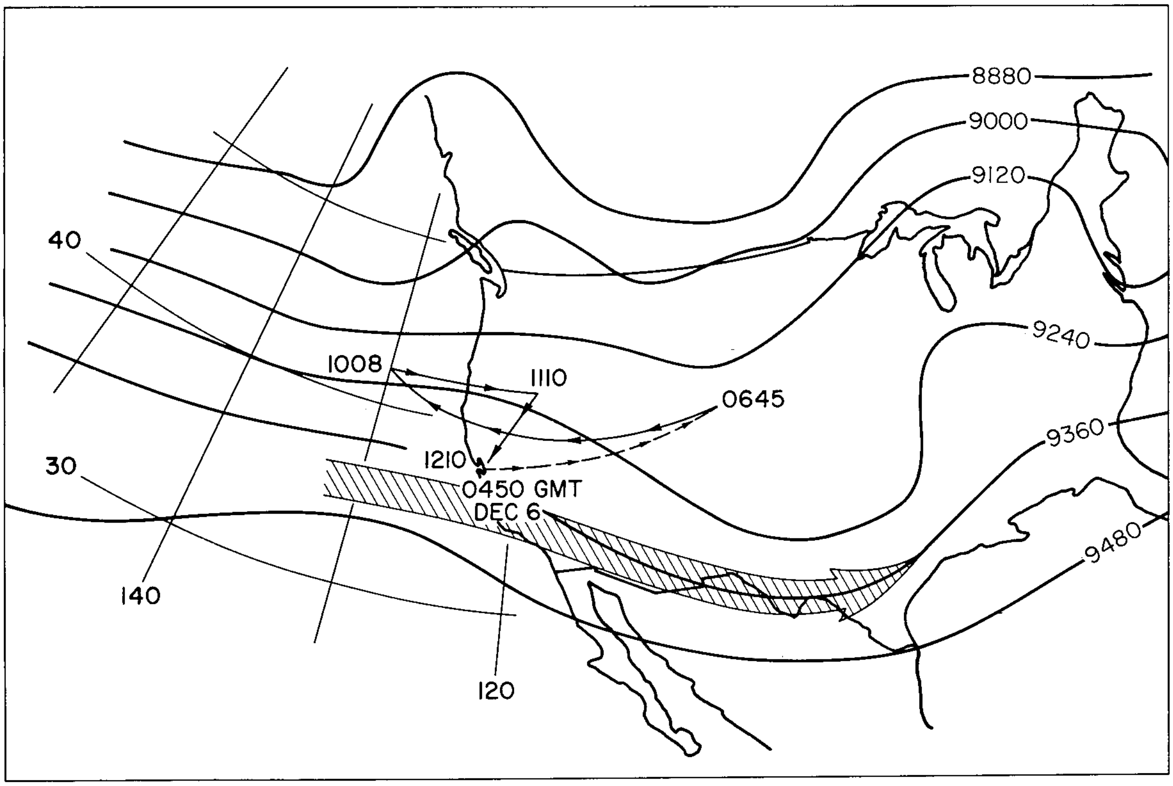
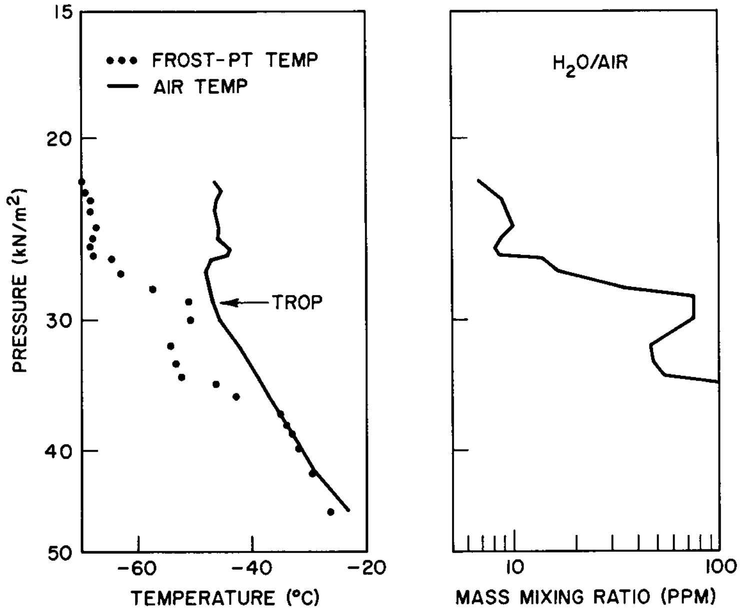


Fig. 3 — The track for the flight December 6, 1974, and the height contours (heights in meters) analyzed for the 30-kN/m^2 surface at 1200 GMT

The in-situ measurements of wind and temperature during the flight determine the position of the flight pattern in the field of motion (Fig. 5). Winds along the westbound flight path backed from 300 to 260 degrees, locating the flight area in a weak ridge between a deep trough in the central United States and another less intense trough to the west. Temperatures along the flight path were near-50°C and slightly colder west of the ridge line than east; the range of variation was not over 5°C. During the final southbound leg of the flight

Fig. 4 — The vertical profile of frost-point temperature and air temperature (left) and the mixing ratio of water vapor to air mass (right) obtained during the initial flight ascend on December 6, 1974



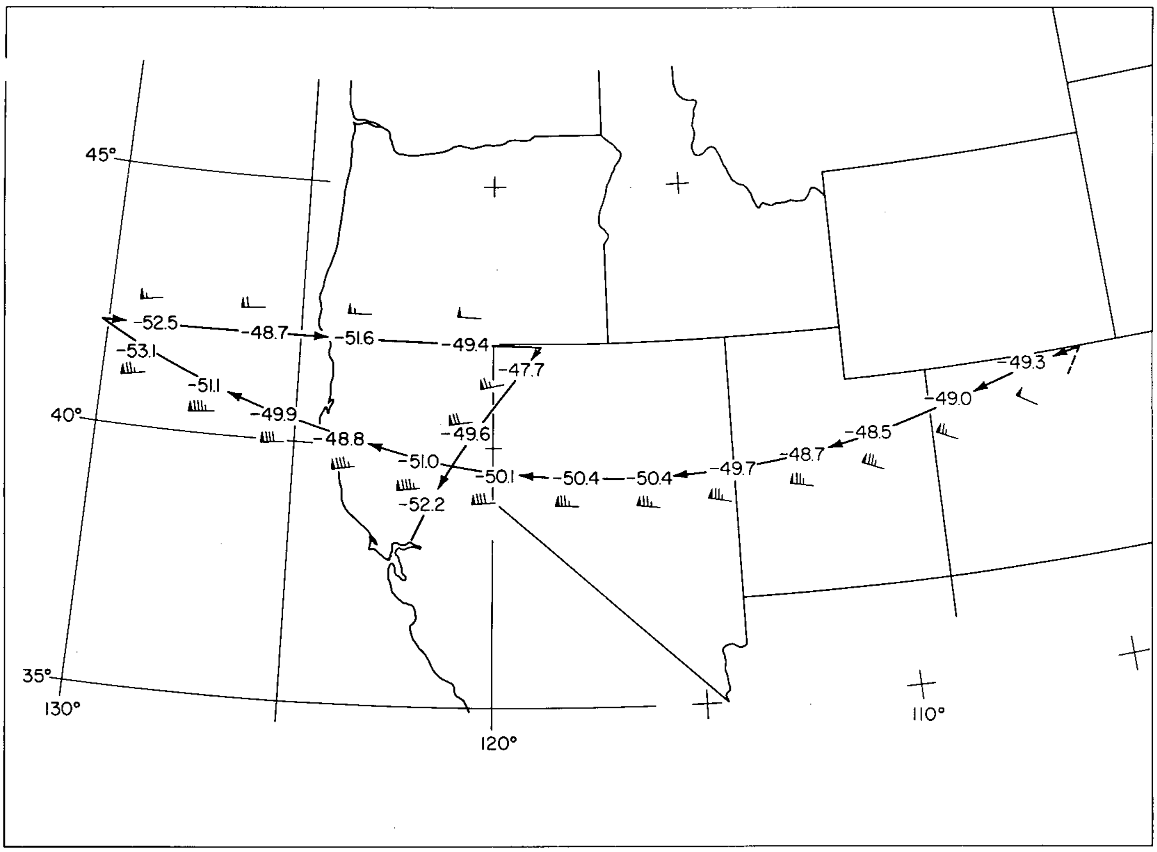


Fig. 5 — Air temperature and wind for 15-minute intervals along the track for the flight of December 6, 1974, at a pressure height of 18.3 kN/m^2

the wind speed increased and temperature decreased as the plane crossed the field of motion and approached the jet stream. During the entire flight the aircraft was north of the jet stream and about 3000 meters above the tropopause.

The lowest mixing ratios (Fig. 6), in the range of 2.0 to 2.3 ppm, were observed during the first half of the westbound flight while the aircraft was flying from the trough to the ridge line when there was a northern component to the winds. West of the ridge line the mixing ratios were higher, in the range of 2.3 to 2.6 ppm, and the winds had a small component from the south. An inverse correspondence between temperature and mixing ratio suggests that vertical motion and the presence of a vertical gradient of mixing ratio accounted for the difference in mixing ratio east and west of the ridge line. This is further supported by measurements during the descent from cruise altitude, which show a mixing ratio increase of 0.2 ppm during the first 300 meters of descent and a more rapid increase of 1.2 ppm during the next 300 meters of descent, indicating that the cruise altitude near Moffett Field was close to or within the layer of transition at the base of the stratosphere.

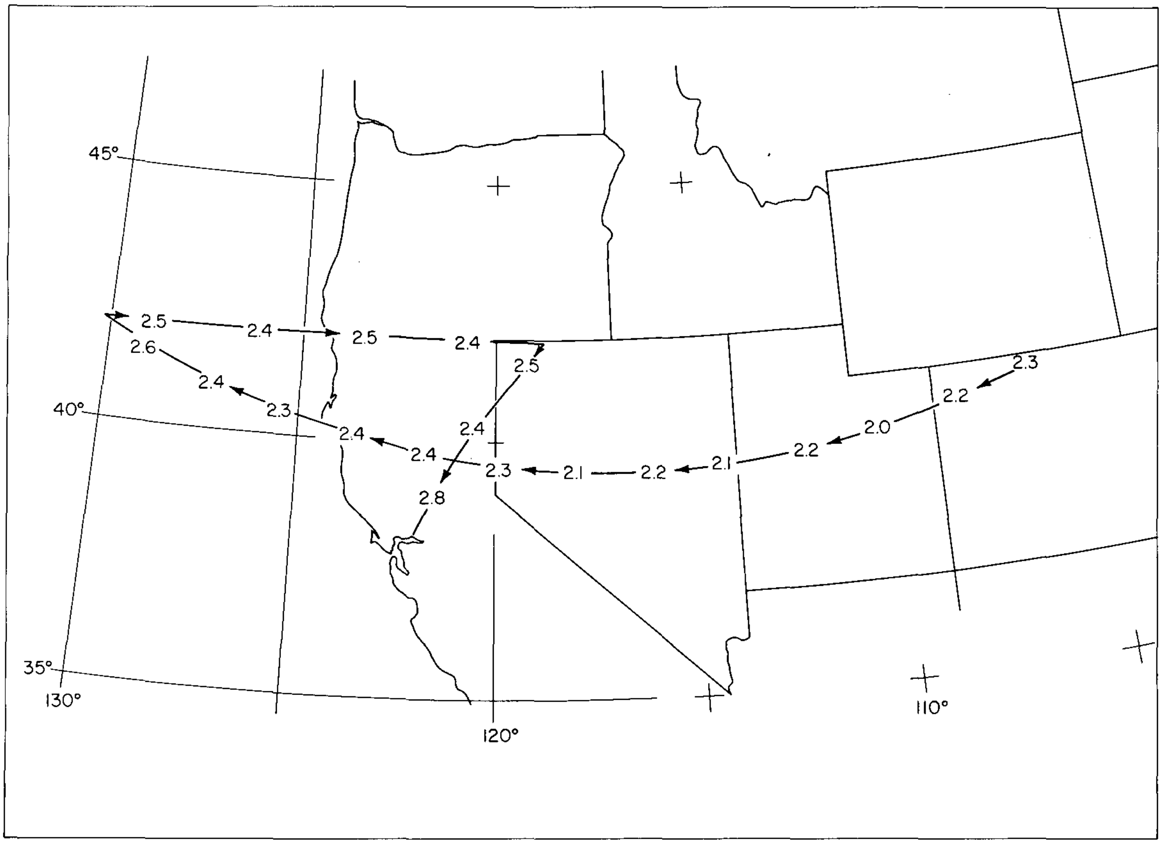


Fig. 6 — The mixing ratio (ppm) of water vapor to air mass for 15-minute intervals along the track for the flight of December 6, 1974, at a pressure height of 18.3 kN/m^2

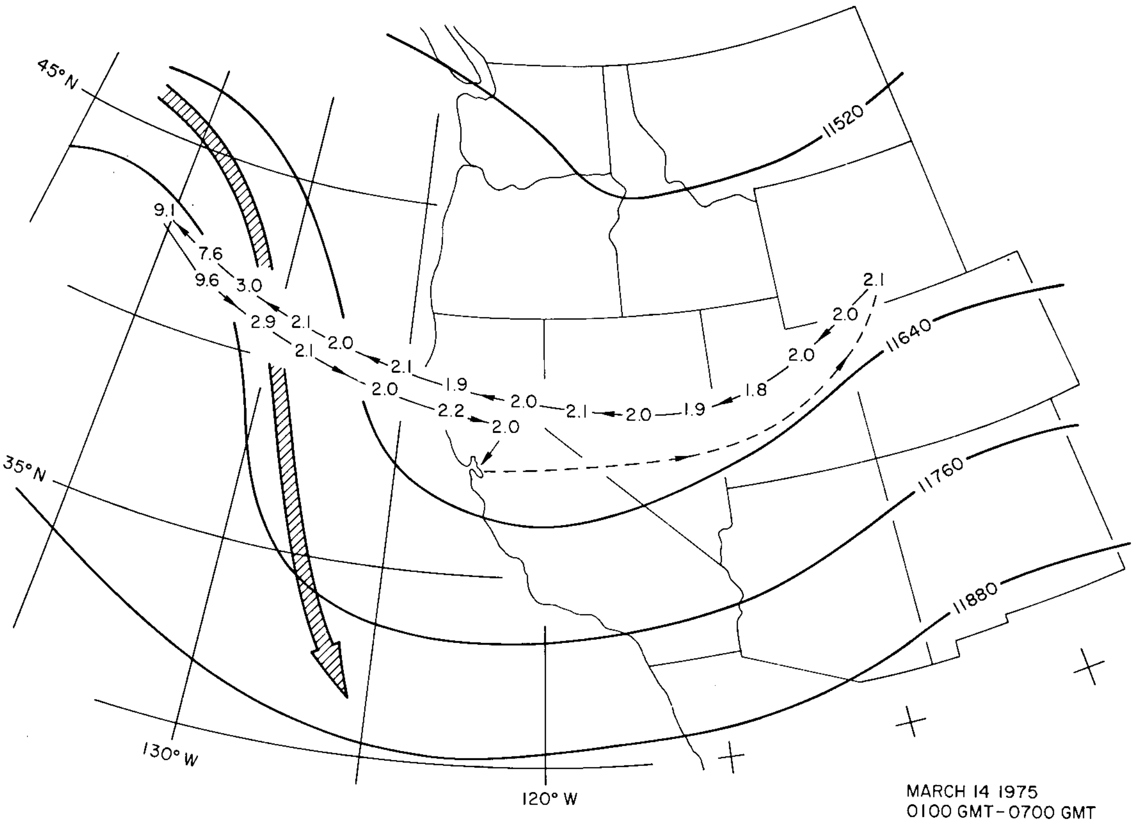


Fig. 7 — Mixing ratio of water vapor to air mass at 15-minute intervals along the track for the flight of March 14, 1975, at a pressure height of 17.8 kN/m^2 (solid track) and the height contours (heights in meters analyzed for the 20-kN/m^2 surface at 0000 GMT. The position of an atmospheric stream is shown as a hatch band.

In view of the close proximity of the cruise altitude to the mixing layer at the base of the stratosphere, it is reasonable to believe that the lower values of observed mixing ratio are most indicative of the stratospheric mixing ratio in the layers immediately above the mixing layer. This flight and the flight on December 4 include-6100 kilometers of flight when the observed mixing ratio was less than 2.6 ppm and within the range of 2.0 to 2.6 ppm.

The December flights were followed by a series of four flights in March 1975. The first of the March flights was on the 14th, when the coastal area was dominated by an upper air trough with an atmospheric jet stream 560 kilometers west of the coast, with the axis paralleling the coast. The flight course was east to Rawling, Wyoming, west to a position 1000 kilometers west of the coast, and east again to Moffett Field. Data collection commenced at Rawling at a pressure height of 17.8 kN/m^2. The water-vapor mixing ratio along the flight path and the height contours of the 20-kN/m^2 surface are shown in Fig. 7. The tropopause pressure was 25 kN/m^2 at Oakland and Denver and 31.8 kN/m^2 at Medford, placing the aircraft 2100 to 3700 meters above the tropopause while over the continent. The water-vapor mixing ratio in the stratospheric region east of the jet stream was in the range of 1.8 to 2.2 ppm. When the aircraft crossed the jet stream from east to west, the air temperature dropped 15°C and the frost-point temperature increased 10°C, resulting in only a 6°C spread between frost-point temperature and air temperature. This near approach to stauration suggest that the flight level was in or close to the troposphere while west of the jet stream.

The flight of March 18 (Fig. 8) was on the western side of an upper air trough, with the atmospheric jet stream traversing the area of flight from northwest to southeast. The jet stream was crossed four times, with flight in the troposphere just below the tropopause when south of the jet stream and in the stratosphere 600 to 900 meters above the tropopause when north of the jet stream.

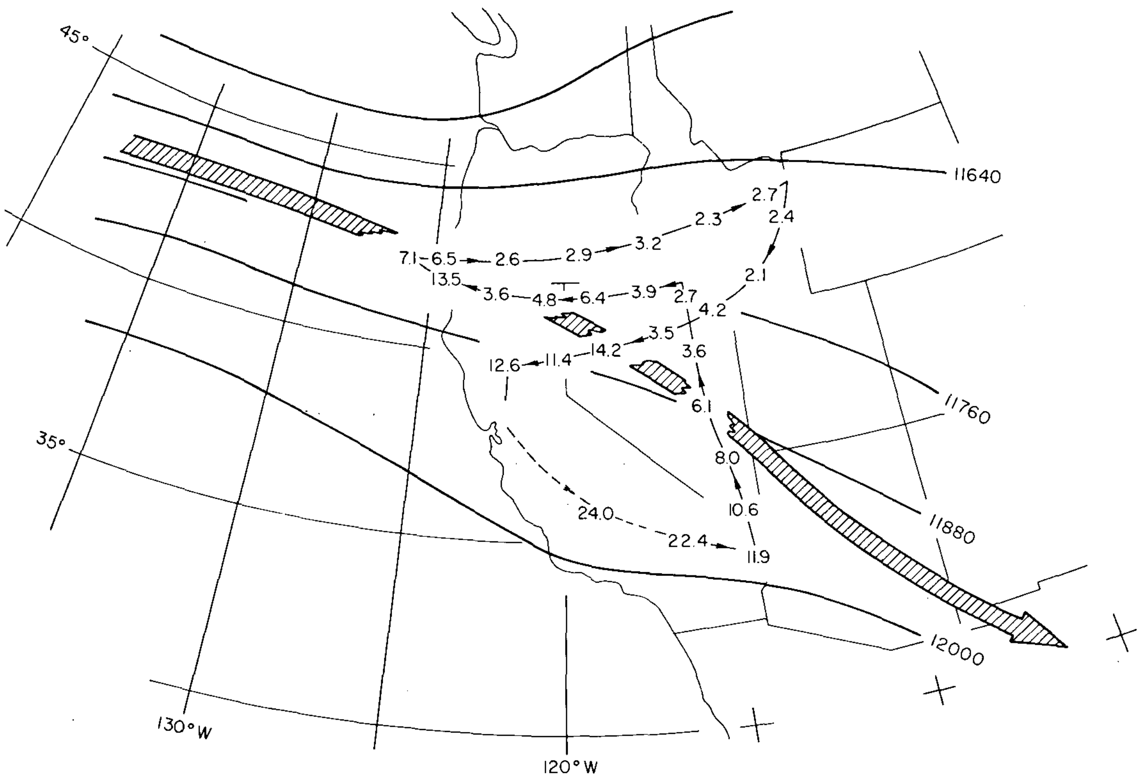


Fig. 8 — Mixing ratio of water vapor to air mass at 15-minute intervals along the track for the flight of March 18, 1975, and the height contours (heights in meters) analyzed for the 20-kN/m^2 surface at 0000 GMT. The position of an atmospheric jet stream is shown as a hatched band. Pressure heights along the flight track are 21.5 kN/m^2 (dashed)

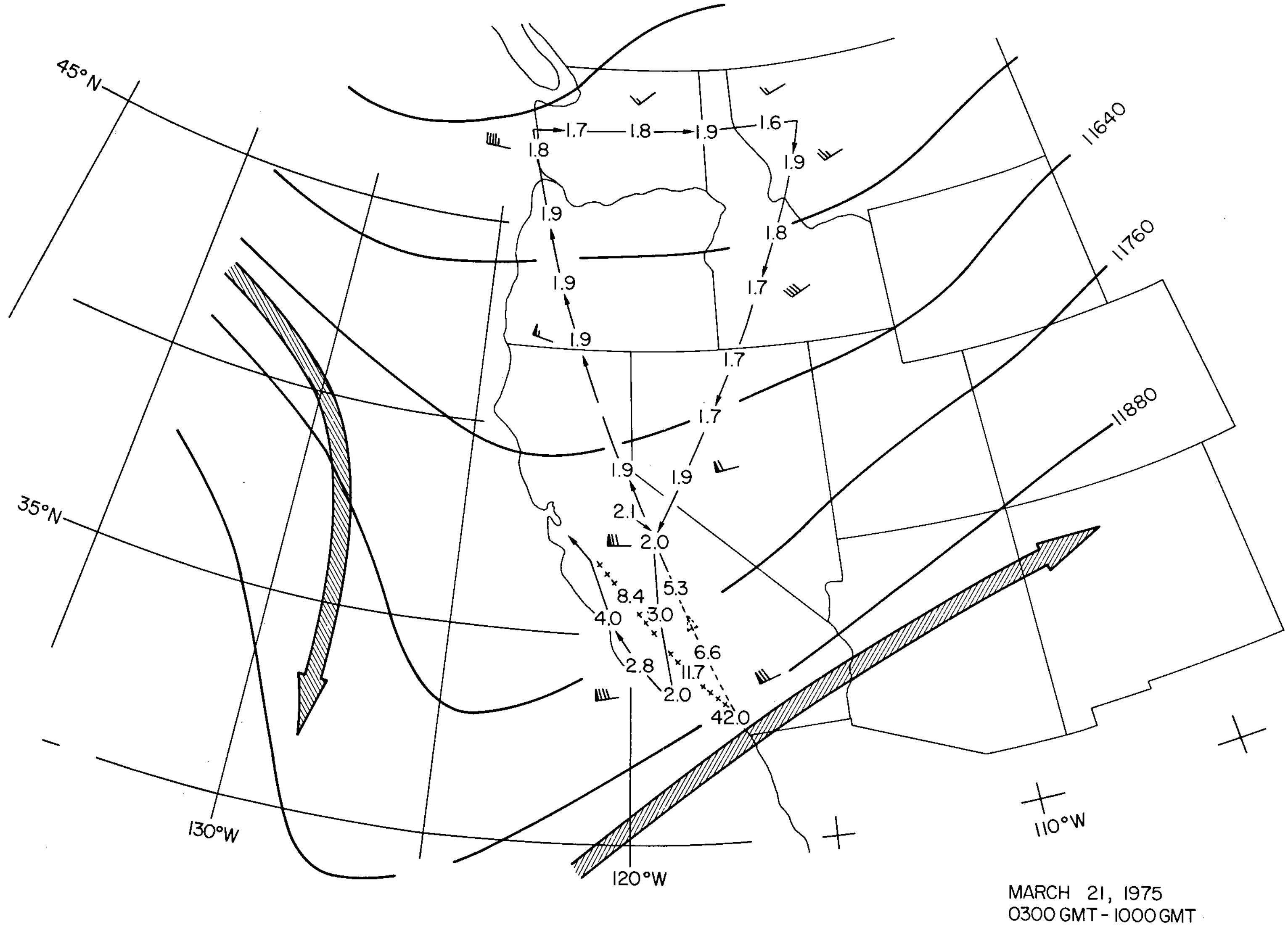


Fig. 9 — Mixing ratio of water vapor to air mass at 15-minute intervals along the track for the flight of March 21, 1975, and the height contours (heights in meters) analyzed for the 20-kN/m^2 surface at 0000 GMT. The position of the atmospheric jet stream is shown as a hatch band. Pressure heights along the flight track are 21.6 kN/m^2 (crossed), 19.6 kN/m^2 (dashed), and 17.8 kN/m^2 (solid).

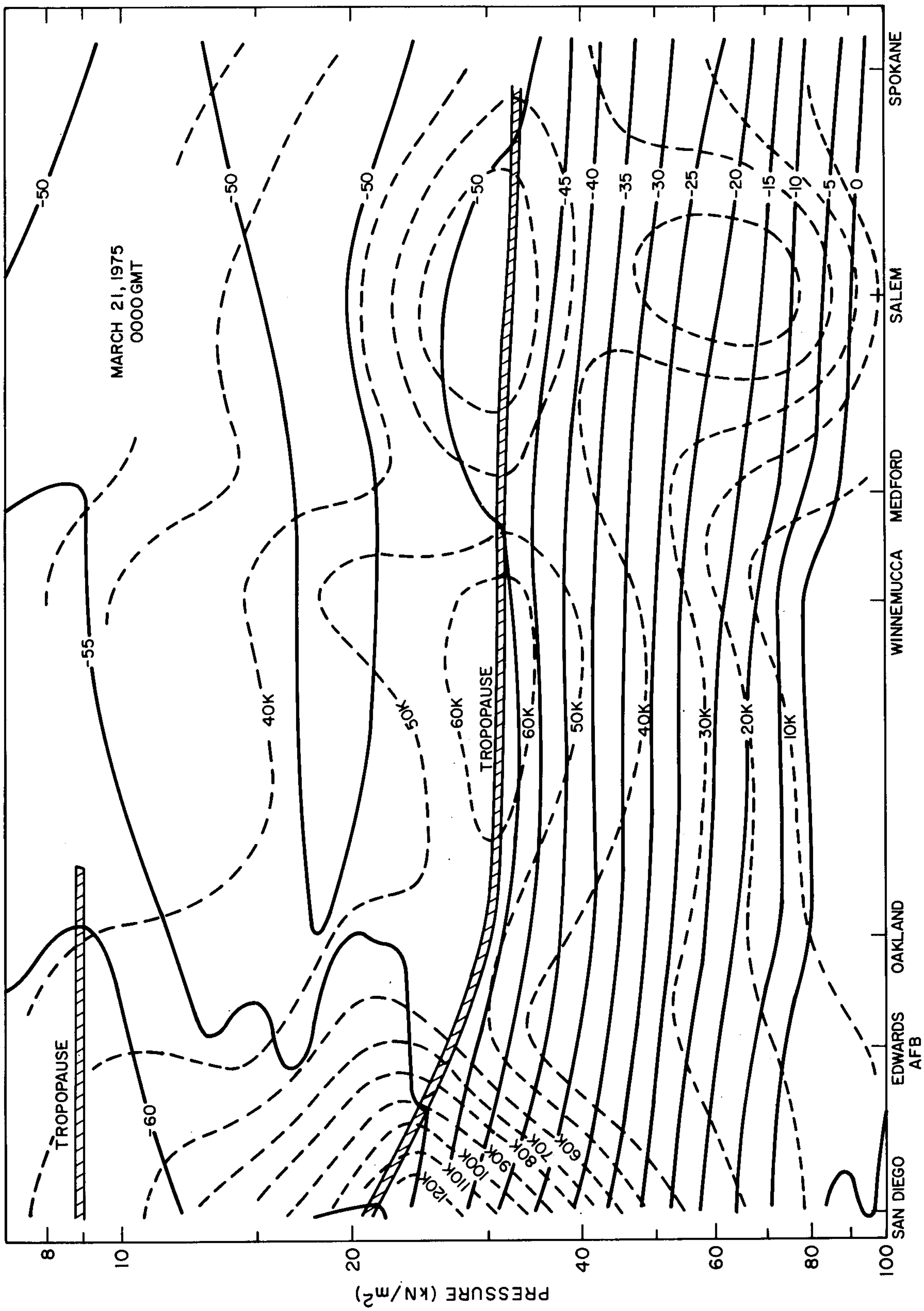


Fig. 10 — A vertical cross section of the atmosphere from San Diego to Spokane showing isolines of temperature (°C), wind speed (knots), and tropopause height (meters)

Saturation conditions prevailed during much of the flight south of the jet stream, with the mixing ratio generally above 10 ppm. Dryer air was encountered to the north of the jet axis as the aircraft entered the stratosphere. When the aircraft was 150 kilometers north of the jet axis, the mixing ratio was at 4 ppm and varied between 2 and 4 ppm northward, where the flight level was never more than 900 meters above the tropopause and where a vertical gradient of mixing ratio is to be expected in the transition region between tropospheric and stratospheric air. The close proximity to the tropopause probably accounts for the high variability which was observed.

The flight of March 21 (Fig. 9) spanned a latitude range of 15 degrees from southern California to Washington in the region of an upper air trough. A cross-section analysis over the route appears in Fig. 10. North of Oakland the tropopause pressures were greater than 30 kN/m^2, which places the flight level more than 3300 meters above the tropopause. Southward from Oakland, the tropopause pressure decreased to 20 kN/m^2 at San Diego and weakened, and a second tropopause at 9 kN/m^2 became more pronounced.

During the initial southbound flight, the aircraft passed through the tropopause from stratosphere to troposphere while flying at 21.6 kN/m^2, and the mixing ratio reached a high of 42 ppm in saturated air. When the aircraft turned northward and changed flight level to 19.6 kN/m^2, it again entered the stratosphere, accompanied by a drop in mixing ratio to 5 to 7 ppm. At 37°N, the flight level was changed 17.8 kN/m^2 for the remainder of the flight, and the mixing ratio dropped below 2 ppm. There followed 2400 kilometers of flight north of this latitude during which the aircraft was more than 3300 feet above the tropopause.

The mixing ratios which were in the narrow range of 1.6 to 1.9 ppm were the lowest observed in the series of flights and showed no systematic latitude dependence as the aircraft twice traversed a 10-degree latitude band. During the final hour of flight the jet stream was again approached but this time at 17.8 kN/m^2. The flight level remained in the stratosphere but approached the tropopause level before the aircraft turned north again for the return to base. The mixing ratio varied erratically between 2 and 4 ppm near the tropopause.

The final flight of the series was on March 28 (Fig. 11) on the western side of a trough with a jet stream again passing through the area of flight. Figure 12 shows the tropopause height contours for the flight region together with the pressure height of the aircraft and the observed mixing ratio at points along the flight path. The tropopause height analysis recognizes only one tropopause level, so that the interpolated contours show a tight gradient across the jet axis, whereas the true situation is an overlap of a tropopause north of the jet axis by a higher tropopause south of the axis with a tropopause discontinuity. The region of tight gradient should therefore be regarded as a region of double tropopause with tropopause discontinuity.

The flight altitude was increased by increments, reaching the highest flight altitude at the Oregon border. The aircraft was in the troposphere during the initial southbound leg of the flight and passed through the tropopause discontinuity into the stratosphere after turning east. During the northbound flight, the aircraft was 1200 to 1800 meters above the tropopause, and the observed mixing ratio was in the range 2.3 to 2.1 ppm. Climbing to the final cruise level of 17.9 kN/m^2, the aircraft turned to the southwest and flew through the tropopause discontinuity again. The mixing ratio was in the low range of 1.9 to 2.0

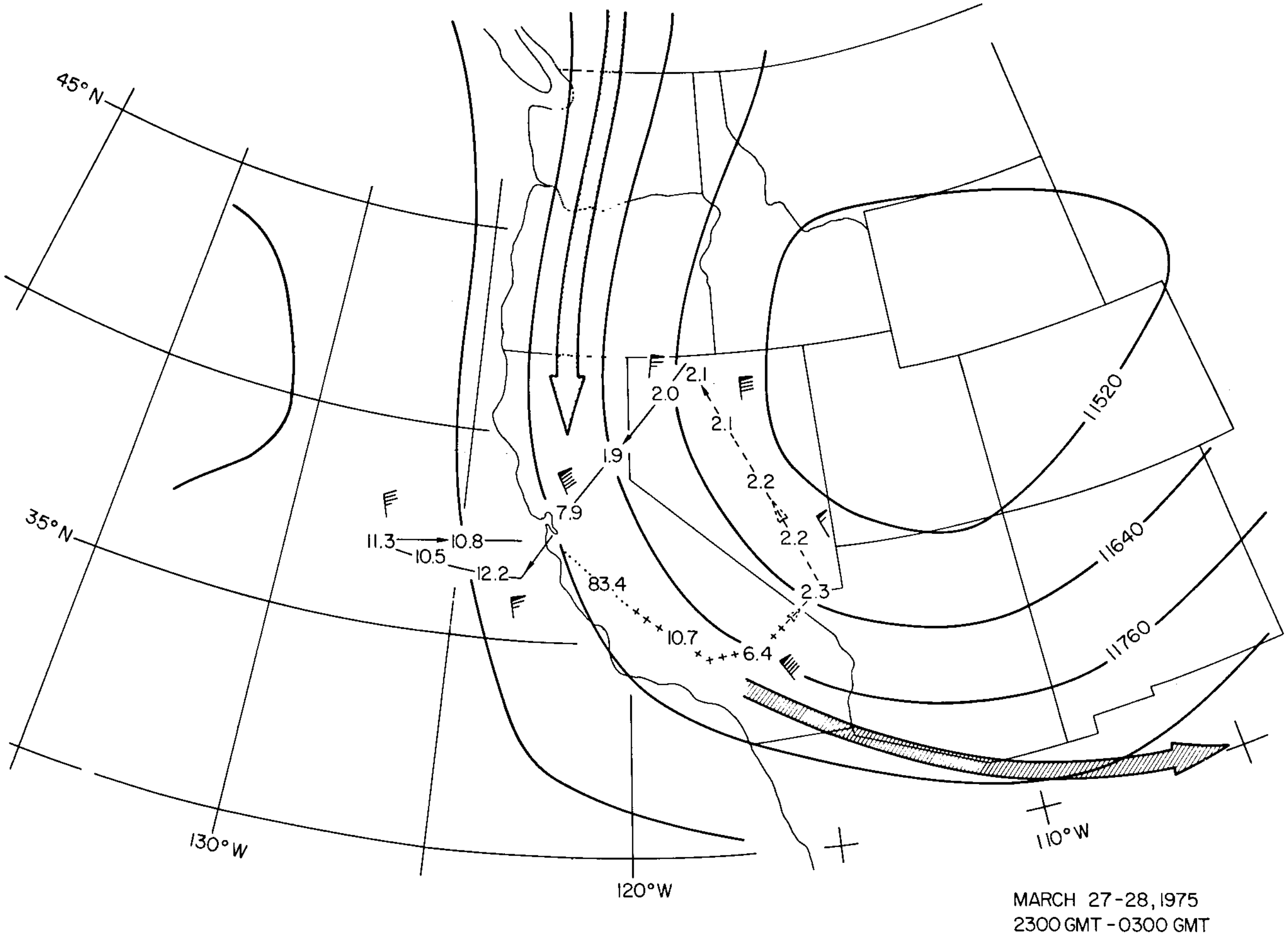


Fig. 11 — Mixing ratio of water vapor to air mass at 15-minute intervals along the track for the flight of March 27-28, 1975, and the height contours (heights in meters) analyzed for the 20-kN/m^2 surface at 0000 GMT March 28, 1975. The position of the atmospheric jet stream is shown as a hatched band. Pressure heights along the track are 31.2 kN/m^2 (dotted), 26.2 kN/m^2 (crossed), 23.8 kN/m^2 (dashed), and 17.8 kN/m^2 (solid).

ppm until the aircraft passed through the tropopause discontinuity. The balance of the flight was in the troposphere on the anticyclonic side of the polar jet stream, where the mixing ratio was greater than 10 ppm and the air was close to saturation.

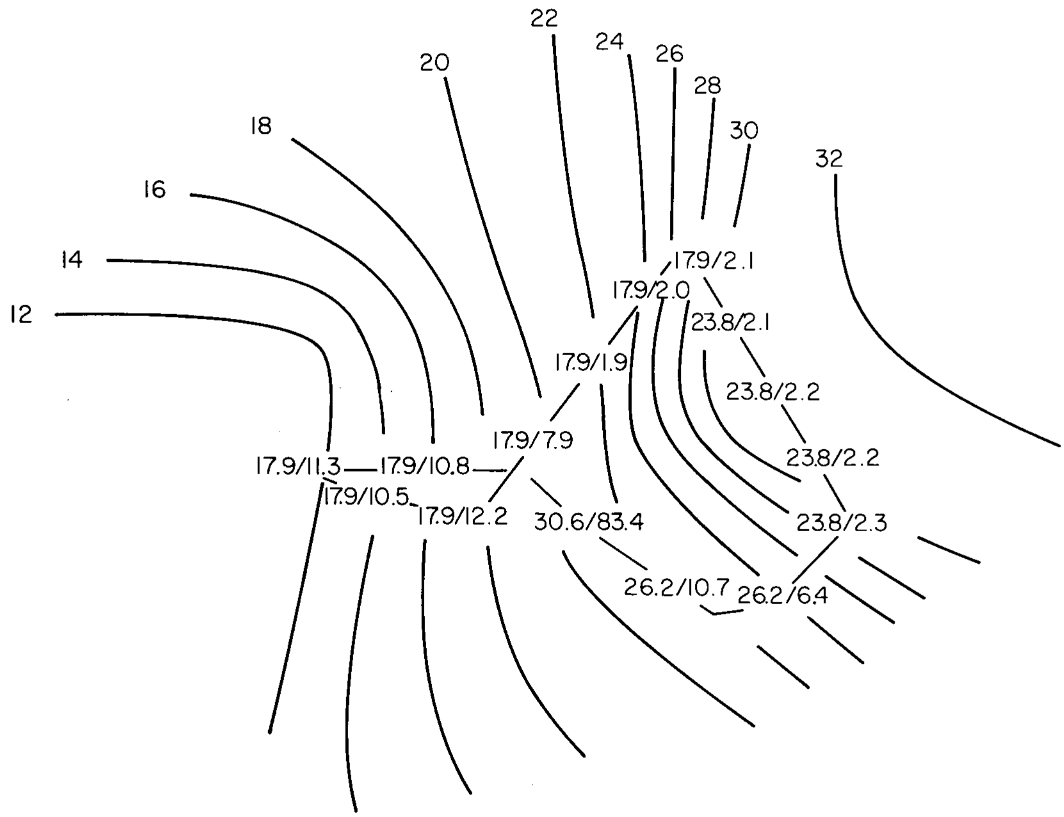


Fig. 12 — Tropopause pressure-height contours analyzed for 0000 GMT March 28, 1975 (contours in kN/m^2) and the pressure height (kN/m^2) and mixing ratio of water vapor to air mass at 15-minute intervals along the track for the flight of March 27-28, 1975.

CONCLUSIONS

The water-vapor concentration in the low stratosphere is known to vary with an annual cycle with a minimum in later winter. The normal winter concentration based on a 10-year data period is 2.4 ppm. The two series of flights in December 1974 and March 1975 provided an opportunity to measure the water-vapor concentration over a broad geographical area at midlatitudes in early winter and again in late winter.

The December measurements in early winter revealed dry regions of the stratosphere with a water vapor concentration that was already below the normal winter concentration. The mixing ratio was observed to be less than 2.6 ppm over 6100 kilometers of flight and between 1.9 and 2.3 ppm over 1600 kilometers of flight.

The March measurements showed a further drying of the low stratosphere, with the concentration of water vapor below 2.1 ppm over 5500 kilometers of flight and in the range of 1.6 to 2.0 ppm over 3500 kilometers of flight. The measurements of March 21 showed a low concentration in the 1.6 to 1.9 ppm range over a 10-degree latitude band north of the polar jet stream and at more than 3300 meters above the tropopause. The concentration showed no systematic variation with latitude.

The measurements over flight paths which were above the tropopause and transition layer showed substantial uniformity over long distances. Typical variability in December was 0.6 ppm about a value of 2.3 ppm, and in March a typical variability was 0.5 ppm about a value of 1.9 ppm.

The measurements show a progressive drying of the stratosphere during the winter of 1974-1975, with concentrations reaching anomalously low values by late winter. The decrease was observed over a broad latitude band and on separate flight dates and so is representative of the midlatitudes generally.

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